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Optical and Current Measurements of Lightning Attachment to the 356-m-High Shenzhen Meteorological Gradient Tower in Southern Coastal Area of China

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ABSTRACT This paper presents in detail the instrumentation for coordinated optical and current measurements of lightning discharges to a 356-m-high meteorological tower and the observation results. The tower, which is located at Shenzhen, a lower latitude coastal city in south China, was equipped with a non-inductive current shunt at its top and a high-speed camera and electromagnetic field sensors at 440 m away from the tower base. A total of 24 discharges to the tower were well documented in the period of April to June of 2019. Three of them were analyzed in detail with the focus being given to the feature of upward leaders initiated from the tower: Case 1 - a connecting upward positive leader (connecting UPL) induced by a downward negative in a downward negative discharge, Case 2 - an upward positive leader (UPL) in the initial stage of an upward negative discharge, and Case 3 - an upward negative leader (UNL) in the initial stage of an upward positive discharge. All the three leaders had a stepping feature during their initial stages, each step producing an isolated but oscillated current pulse with a time scale of 1 μs. The connecting UPL had 5 steps during its initial 2.6 ms, with a step interval ranging in 0.1$\sim$1.5 ms and a current pulse peak in 1$\sim$5 kA. The UPL had also 5 steps but during its initial 200 μs, with a step interval ranging in 20$\sim$50 μs, a step length in 0.8$\sim$2.2 m, a current pulse peak in 0.5$\sim$2.2 kA, and a leader average speed in 0.4$\sim$1.1 $\times$ 10^5 m/s. The UNL had 8 steps during its initial 104 μs, with a step interval ranging in 13.6$\sim$22 μs, a step length in 3.9$\sim$7.1 m, a current pulse peak in 2.3$\sim$12.5 kA, and a leader average speed in 1.9$\sim$6.6 $\times$ 10^5 m/s.

INDEX TERMS Lightning discharge, tall tower, upward leader, lightning current.

I. INTRODUCTION

Lightning is an energetic atmospheric discharge phenomenon associated with high current, high voltage, strong and transient electromagnetic radiation that occurs inside thunderclouds or between the cloud and ground [1]. Lightning current measurement plays a vital role in the study of lightning physics and its effects to ground objects like buildings and various electrical and electronic systems, and in the design of lightning protection devices.

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A lightning discharge attaches "randomly" to ground, making the direct measurement of the lightning current a big challenge to conduct. There are two basic approaches to obtain the lightning current directly. One is the current measurement at the channel base of a rocket-triggered lightning discharge during overhead thunderstorms [2]–[4]. Another is the current measurement on a tall structure (e.g., high buildings, towers, windmills, etc.) at its top or ground base when a lightning discharge attaches to it [5]–[7]. In both cases, either Rogowski coil/ Pearson coil or a low-resistance current measuring shunt was applied. Notably, the lightning current measurement on tall towers has been carried out in many countries during the past decades, such as, Peissenberg Tower in Germany [8], Gaisberg Tower in Austria [7], Skytree Tower in Japan [6], Morro do Cachimbo Station in Brazil [5], and Säntis Tower in Switzerland [9]. Detailed characteristics of lighting currents associated with upward discharges in different regions around the world were reported in literature [10]–[14]. It is noted that all the tall tower lightning current measurements were conducted in either higher latitude areas or inland regions. There is big gap in understanding the current characteristics of lightning discharge to tall structures over a lower latitude and coastal area, where strong thunderstorms often happen [15].

To make further contributions to the current measurement of lightning discharges to ground objects, especially in lower latitude coastal regions, we have set up a lightning current measuring system at the top of the Shenzhen Meteorological Gradient Tower (SZMGT) in southern coastal region of China, which is a 356 m high steel structure tower built in 2016. This is a region where thunderstorms come from both inland and oceanic areas frequently, and thus the current measurements on SZMGT may enable us to get more insight of the characteristics of lightning currents in a lower latitude coastal region. Besides the current measurement system on the top of SZMGT, there were also a high-speed camera and electromagnetic field sensors deployed at an observation site 440 m away from the tower base. With these observations, more details of a lightning discharge can be obtained, such as the behavior of an upward leader and the attachment process [16]. Upgrades on both hardware and software of the observation system have been conducted continuously during past three years to ensure the system being stable and reliable.

In this paper, we present the results of very recent observations in early 2019. In the following sections, we present firstly in detail the SZMGT current measurement system setup and then the observation results. During the period of April to June of 2019, a total of 24 lightning discharges to SZMGT were well documented with the current measuring system and the high-speed camera. Among them, 5 were downward negative discharges with one or multiple return strokes, 2 were upward negative discharges with one or multiple return strokes, and 17 were upward flashes with no return stroke. The peak currents for those with return strokes ranged from −7.9 kA to −75.4 kA. In following sections, three of them (one downward flash, one upward flash with return stroke and one upward flash with no return stroke) will be analyzed in detail to demonstrate preliminary results of observations of lightning discharges to SZMGT.

II. LIGHTNING OBSERVATION SETUP

A. SHENZHEN METEOROLOGICAL GRADIENT TOWER

The Shenzhen Meteorological Gradient Tower (SZMGT) was built in May of 2016 in the suburban area of Shenzhen, China (**Fig. 1**), which is located in a lower latitude coastal area at (22.65° N, 113.89° E). The height from the tower tip to the ground level is 360.8 m (356 m for the tower body with a 4.8 m high lightning rod). It was built originally for meteorological applications, such as the observation of conventional meteorological and atmospheric environmental parameters in the earth surface boundary layer.

FIGURE 1. Photo of the 356 m high Shenzhen Meteorological Gradient Tower (SZMGT), showing the main steel structure of the tower and the steel stray lines for fixing and securing the tower. The photo on the upper right corner shows the current measurement and data transfer devices enclosed in a shielding case on the tower top.

To take advantage of the tower, it was equipped with specially designed facilities for investigating lightning discharges to the tower during thunderstorms. Those facilities included a 0.25 mΩ current shunt system installed at the tower top position (just below 356 m) between the lightning rod and the tower body and a batch of instruments located 440 m away from the tower base for measuring the optical and electromagnetic signals from the discharge to the tower. A detailed illustration of the current measuring system and the other instruments is given in next section. All measuring systems were synchronized by GPS systems with a time uncertainty of about 100 ns.

B. INSTRUMENTATIONS ON AND AROUND SZMGT

Fig. 2 illustrates the instruments installed on and around SZMGT. According to the instrument functions, they can be grouped into four functional parts, as marked by the four dashed rectangles in **Fig. 2**(a).

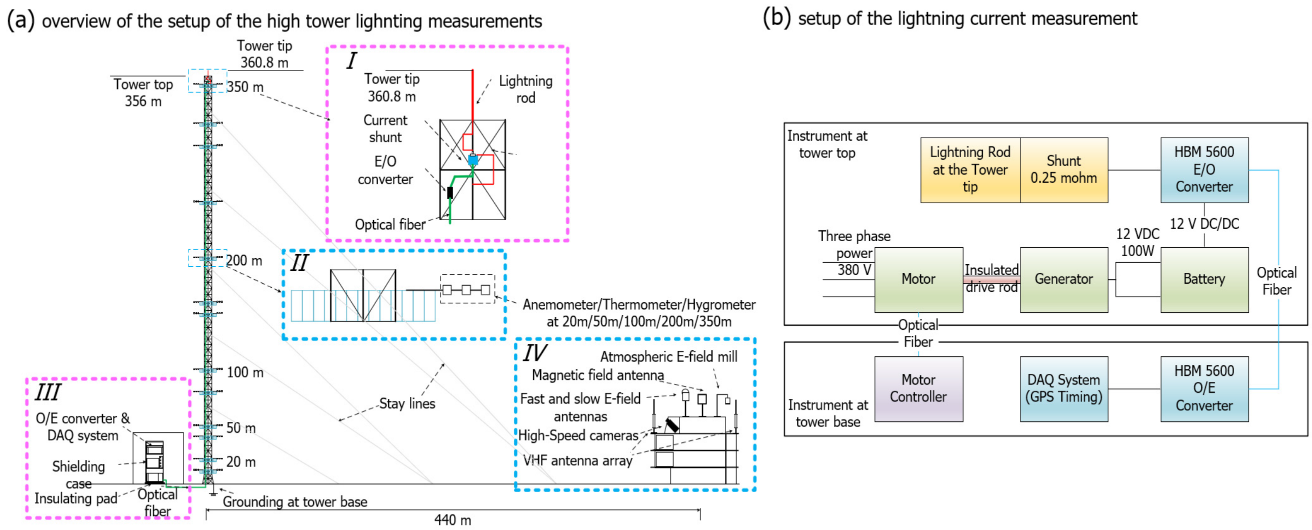

FIGURE 2. Setup of the lightning current and other measurements on and around SZMGT. (a) Overview of the instrumentation setup, including four functional parts: I. The current shunt system on the tower top, II. Ordinary atmospheric parameter measurements along the tower, III. The data acquisition system on ground near the tower base, and IV. The instruments deployed at 440 m away from the tower base. (b) The setup of the power supply and data acquisition systems for parts I and III.

Part I shows the setup on the tower top, which including a 4.8 m high lightning rod standing on the tower top above a metallic equipment case with its lower end inside the case (the small photo on the upper-right in **Fig. 1**). The metallic case is with an insulation sleeve that insulates the lightning rod from the case. Inside the case is a 0.25 mΩ current shunt (Hilotest ISM500, bandwidth DC$\sim$50 MHz) installed between the lightning rod and the tower body. The current output was connected to optical fibers via an HBM 5600 E/O converter inside the case.

Part II shows an example of the anemometers, thermometers and hygrometers installed at 20-m/50-m/100-m/200-m and 350-m high positions of the tower, for ordinary gradient observations of meteorological parameters.

Part III illustrates the setup inside a well-shielded and insulated operation cabin on ground at 20 m away from the tower base. Optical fibers down from the tower top were connected to an HBM 5600 O/E converter and a data acquisition system (HBM Gen 7tA, 100 MHz sampling rate) inside the cabin.

Part IV shows other observation systems in the main observation site at 440 m away from the tower base, which included: 1) a high-speed camera (Phantom V711) pointing to the tower tip (running at 96,000 fps with an inter-frame interval of 10.41 us and a frame exposure time of 9.81 us), 2) a slow electric field antenna (with a bandwidth of 0.18 Hz-3.2 MHz and a sampling rate of 10 MS/sec), 3) a fast electric field antenna (with a bandwidth of 100 Hz-3.2 MHz), 4) an atmospheric electric field mill, 5) a magnetic field antenna, and 6) a VHF antenna array. Due to a medium wave radio tower located 200 meters away from the main observation site, measurements of the fast electric field, the magnetic field and the VHF array were significantly contaminated. For this sake, analyses of lightning observation results in this study will be focused on the measurements of the current, the high-speed camera and the slow electric field.

Shown in **Fig. 2**(b) is the setup of the power supply and data acquisition and transfer devices for the lightning current measuring system on the tower top. These devices were deployed at two places, the metallic case at the tower top and the operation cabin on the ground near the tower base. Since the E/O converter and current shunt inside the metallic case on the tower top were directly connected, insulations between the power supply of the E/O converter and other parts of the measuring system became very necessary. For this, we used an AC motor to drive another electric generator through an insulator to charge a battery group that supplies power to the E/O converter.

III. OBSERVATION RESULTS OF LIGHTNING DISCHARGE TO SZMGT

From April to June of 2019, a total of 24 discharges to SZMGT were documented with both the lightning current measuring system and the high-speed camera. Among them, 5 were downward negative discharges initiated by a downward negative leader (DNL) with single/multiple return stroke processes, 2 were upward negative discharges initiated by an upward positive leaders (UPL) with single/multiple return strokes processes, and 17 were upward discharges initiated by either an upward negative leader (UNL) or an UPL with no return stroke process. Here we present three examples: Case 1 – a downward negative discharge initiated by a DNL with a connecting upward positive leader (connecting UPL) and single return stroke, Case 2 - an upward negative discharge initiated by an UPL with an initial continuous current process (ICCP) followed by four return stroke processes, and Case 3 - an upward positive discharge initiated

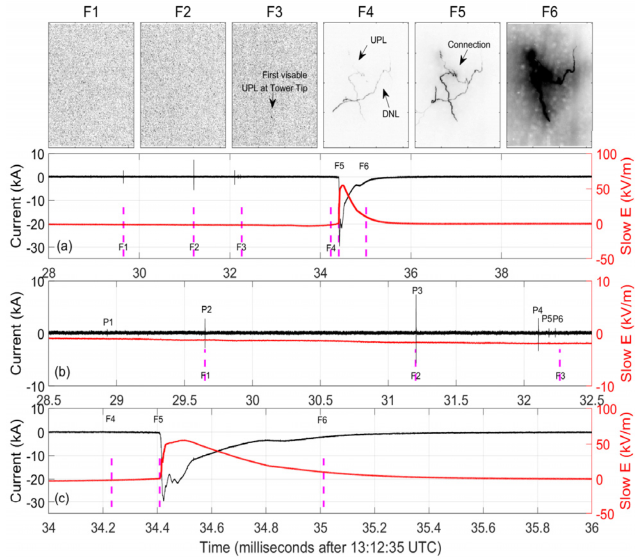

FIGURE 3. Case 1 - A downward negative discharge initiated by a downward negative leader (DNL) with a connecting upward positive leader (connecting UPL) from the tip of SZMGT followed by a return stroke, at 13:12:35 UTC on May 20, 2019. Panels F1 and F2 are 2 camera image frames corresponding to two big leader current pulses, F3 is the first frame when the UPL became visible, and F4 to F6 are 3 frames before, around and after the moment of the DNL connected to the UPL. Panel (a) shows an overall view of the currents (black) measured at the top of the tower and the electric fields (red curve) measured at 440 away from the tower base. Panel (b) is a zoom-in view of panel (a) on the UPL initiation stage, where P1 to P6 indicate the 6 leader current pulses before the first visible frame of the UPL. Panel (c) is a zoom-in view of panel (a) on the return stroke process. Vertical dashed lines stand for the times corresponding to each of the 6 frames F1-F6.

by an UNL with no return stroke process. The focus will be given to the property of initial upward leaders from the tower in the three cases based on simultaneous measurements of the current, electric field and the camera.

A. CASE 1 – A DOWNWARD NEGATIVE DISCHARGE INITIATED BY A DNL WITH A CONNECTING UPL AND A RETURN STROKE

Shown in **Fig. 3** are the results of currents measured near the tower top and the electric field changes and high-speed camera images observed at 440 m away from the tower base, for a downward negative discharge to SZMGT at 13:12:35 UTC on May 20, 2019. Based on images of the high-speed camera, this discharge was initiated with a bright DNL followed an optically weak connecting UPL and a bright return stroke. In the figure, F1 and F2 were two camera image frames corresponding to two big isolated leader current pulses, F3 was the first frame when the connecting UPL became optically visible, and F4-F6 were three frames before, around and after the moment of the DNL connecting to the UPL, respectively. The F1-F3 were enhanced by increasing the brightness (16 times) for easily identifying the leader channel. It can be seen clearly that the connection occurred between one branch tip of the DNL and the lateral surface of the UPL. **Fig. 3**(a) is an overall view of the current and electric field change measurements for this discharge, **Fig. 3**(b) is a zoom-in view of **Fig. 3**(a) for the UPL initiation process and **Fig. 3**(c) a zoom-in view for the return stroke process.

In reference [17], the behavior of upward connecting leaders in lightning discharges to tall buildings with high-speed cameras was well studied. They found that the manner of an upward connecting leader attaching to a downward leader could be grouped into different types. The present case is the type that the DNL tip connected to the lateral surface of the connecting UPL. It is the approaching of the DNL that enhanced the electric field around the tower tip, leading to the initiation of the connecting UPL. Therefore, the DNL development had significant influences on the development of the connecting UPL. It was noted that during the first 2.6 ms of its initiation, the connecting UPL was hardly seen by the camera but well ''seen'' by the current shunt with 6 evident current pulses being recorded (**Fig. 3**(b)), but the first visible frame of the UPL emerged at the tower tip about 30 us after the sixth current pulse. This could be due to that the first six current pulses were induced by the stepping of the DNL rather than by the stepping of the connecting UPL itself. This would be supported by our observation that very little continuous current was recorded during the early stage of the connecting UPL. Nevertheless, it suggests the much weaker luminosity of the UPL comparing to the DNL (the brightness was enhanced 16 times to make the UPL visible in **Fig. 3**F3). The 6 leader current pulses were with a time scale of about 1 μs, an inter-pulse time interval of 0.1$\sim$1.5 ms and a peak value of 0.5 kA, 3 kA, 5 kA, 3 kA, 1 kA, and 1 kA, respectively. Very little continuous currents were recorded during the early stage of this UPL. The return stroke current was measured with a front rise-time of 6 μs, a half-width time of 94.5 μs and a peak value of -29.7 kA.

B. CASE 2 –AN UPWARD NEGATIVE DISCHARGE INITIATED BY AN UPL WITH AN ICCP FOLLOWED BY FOUR RETURN STROKES

Shown in **Fig. 4**is an upward negative discharge initiated by a UPL with an ICCP from SZMGT followed by four return stroke processes, at 12:48:43 UTC on 21 May of 2019. It was an upward discharge triggered by a nearby lightning process.

Fig. 4 (a) shows the simultaneous measurements of the current (black curve) at the tower top, the electric field change (red curve) at 440 m away from the tower base, and the channel brightness (blue curve) near the tower tip, and **Fig. 4** (b) one frame of the lightning channel within the field view of the camera during the initial stage, for Case 2. As can be seen from **Fig. 4** (a), there are 5 significant impulsive current processes, which represent the initial UPL and continuous current process (labeled ICCP) and the four subsequent return-stroke processes (labeled P1, P2, P3, and P4), respectively.

Fig. 4 (c) is a zoom-in view of the ICCP in **Fig. 4** (a), for the initial UPL and continuous current process for Case 2. ICCP is one typical characteristic of the initial stage of upward discharges from towers or rocket-triggered lightning discharges [14], [18], [19]. As can be seen from **Fig. 4**, the UPL was

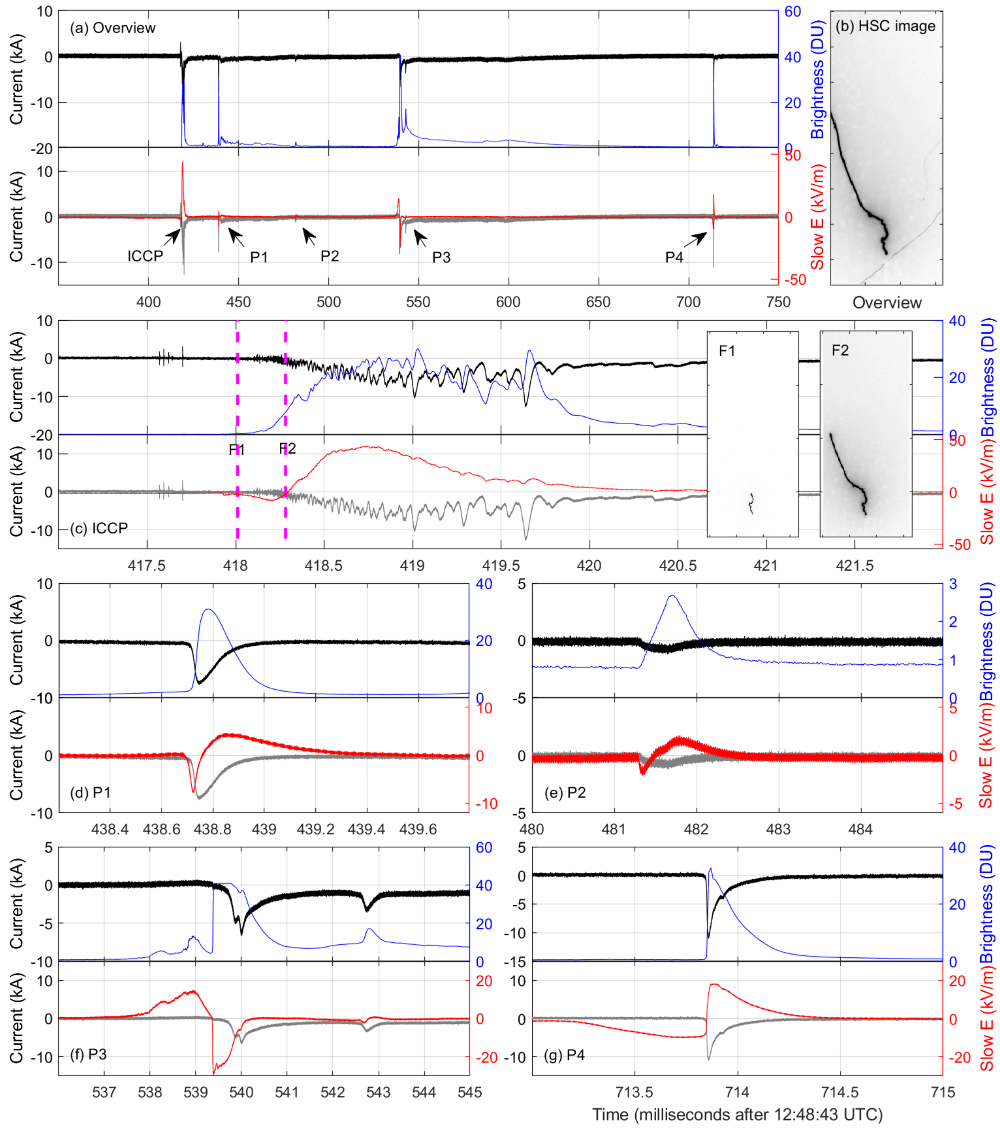

FIGURE 4. Case 2 - An upward negative discharge initiated by an UPL with an initial continuous current process (marked as ICCP) from SZMGT, followed by four return-stroke processes (marked as P1, P2, P3 and P4 respectively), at 12:48:43 UTC on 21 May of 2019. (a) An overview of the current (black curve) at the tower top, the electric field change (red curve) at 440 m away from the tower base and the channel brightness (blue curve) near the tower tip for this discharge. (b) An overview of the UPL channel. (c) - (g) A zoom-in view of the measurements in (a) for the ICCP, P1, P2, P3 and P4, respectively.

initiated with 5 successive current pulses, which had a time scale of about 1 μs, an inter-pulse time interval of 20$\sim$50 μs and a peak current value of 0.5$\sim$2 kA. A detailed discussion on characteristics of the channel luminosity associated with these 5 leader current pulses in the early stage of this UPL will be given in Section 3.3. About 300 μs after the 5$^{\text{th}}$ initial leader current pulse was the ICCP, which lasted about 3 ms. As can be seen from the brightness curve (blue curve) of the channel near the tower tip, the UPL became luminous with the start of the ICCP and kept bright during the whole ICCP period. Two camera frames (F1 & F2) of the UPL channel during the ICCP are also shown on the right of **Fig. 4** (c) with their times marked by two magenta dashed vertical lines (labelled F1&F2) in the figure, to illustrate the development of the UPL channel. Like those reported in the literature and that in Case 1 in this study, there is also no obvious leader branch that can be identified for this UPL. The ICCP included several tens of slow current pulses (peaks ranging in 1$\sim$10 kA) superposed on a continuous changing current component. It was noted that the current pulses during the initial stage of this UPL were almost one order larger than those during the initial UPL stage of a rocket-triggered lightning discharge [3], which could be due to the difference in triggering conditions between an UPL from the tip of a standstill tower and that from the tip of an ascending rocket/wire.

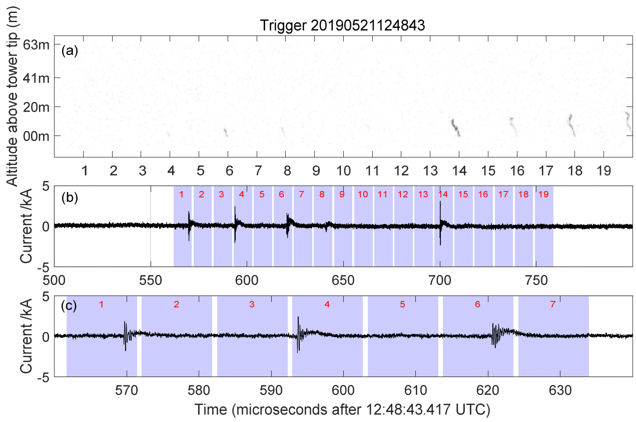

FIGURE 5. **The channel developments and current waveforms during the initial 200 μs of the UPL in Case 2. (a) The channel luminosity developments of 20 successive frames of camera images during the initial 200 μs stage of the UPL, no camera image enhancement was applied. (b) The 5 current pulses during the initial 200 μs stage of the UPL and their corresponding frames of camera images marked by the light purple background. (c) A zoom-in view of (b) for the first 3 current pulses during the first 80 μs and their corresponding camera image frames for the UPL.**

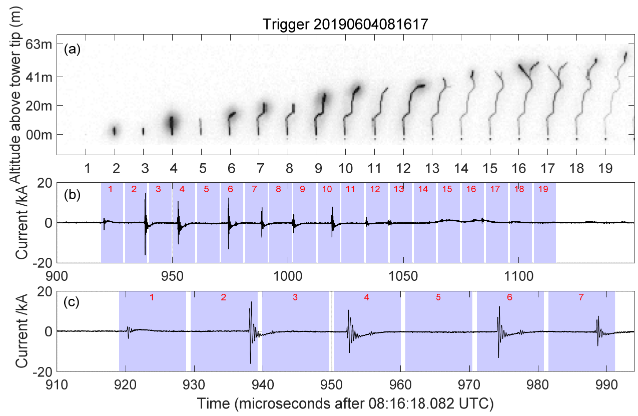

FIGURE 6. **Case 3 - An upward discharge involving only an UNL process from SZMGT at 08:16:18 UTC on 04 June of 2019. (a) The channel luminosity developments of 19 successive camera image frames during the initial 200 μs of the UNL, no image enhancement was applied for easy comparison with Figure 5(a). (b) The current waveforms during the initial 200 μs of the UNL and the corresponding camera frames marked by the light purple background. (c) A zoom-in view of the current waveform in the first 70 μs stage and the time windows of the corresponding 7 camera image frames of the UNL.**

C. THE FEATURE OF INITIATION STAGE OF THE UPL IN CASE 2

In Section III.B for Case 2, we found that a current pulse burst accompanied the initiation of the UPL. We now analyze in detail the development of leader channel luminosity during the first 200 μs (a total of 19 camera image frames) of the UPL initiation stage, as illustrated in **Fig. 5**.

Fig. 5(a) shows the channel luminosity development of 20 successive camera image frames during the first 200 μs of the initiation stage of the UPL, where each frame lasting 10.41 μs with an exposure time of 9 μs and inter-frame dead time of 1.41 μs. **Fig. 5**(b) shows the records of the lightning current and the time windows of the 19 frames for the first 200 μs of the UPL, which consisted of 5 evident current pulses with a time scale of about 1 μs and a peak value of 1.7 kA, 1.9 kA, 1.2 kA, 0.5 kA and 2.2 kA, respectively.

Fig. 5(c) is a zoom-in view of (b) for the first 3 current pulses. As can be seen from these figures, all current pulses presented an oscillation feature, probably due to the complicated impedance feature of the tower. Each current pulse was closely associated with a transient enhancement in luminosity and a step advancement of the leader channel, except for the first current pulse. The first current pulse might be associated with an attempted leader process near the tower tip, which was optically too weak to be seen by the camera. Such an association between the current pulse and the channel development for an UPL in the initial stage of a rocket-triggered lightning discharge was also observed [20]. Although the channel luminosity of this UPL was weaker than that of the upward negative leader that will be shown in the next section in this study, it seemed that a stronger current pulse was usually associated with a stronger luminosity during the leader development.

The stepping signature of this UPL during its initial stage can be identified from both the evolution of channel luminosity and the impulsive signature of the current. As shown in **Fig. 5**(a), this UPL advanced 16.5 m from the tower tip upward in the first 200 μs stage. The average leader propagation speed was estimated to range from 0.4 to 1.1 $\times$ 10^5 m/s with a mean value of 0.8 $\times$ 10^5 m/s, and the step length was in the range from 0.8 to 2.2 m, for the 5 steps during the first 200 μs of this UPL initiation stage, which are well consistent with previous reports on other UPLs [20]–[23].

D. CASE 3 – THE FEATURE OF INITIATION STAGE OF THE UNL IN AN UPWARD POSITIVE DISCHARGE WITH NO RETURN STROKE

Comparing to UPL, studies on UNL from grounded objects were still limited. There were only a few successful simultaneous measurements of optical and current signals of UNL, including one in a tower-initiated upward positive discharge [24] and one in a rocket-triggered upward positive discharge [25]. Here, we present an UNL process initiated from SZMGT at 08:16:18 UTC on 04 June of 2019, which had no subsequent return-stroke process followed, as shown in **Fig. 6**.

Fig. 6(a) shows the channel luminosity development of 19 successive camera frames during the initial 200 μs stage of the UNL in Case 3. Each frame had an exposure time of 9 μs and inter-frame dead time of 1.41 μs. Comparing to the UPL in Case 2, this UNL had much stronger optical emissions during its initial stage.

Fig. 6(b) shows the leader current waveforms during the initial 200 μs of this UNL with the corresponding camera image frames marked by the light purple background. Both **Fig. 6**(a) and (b) show that this UNL had a clear stepping and branching signature during its initial stage, each stepping process corresponding to a current pulse that was superposed on a weak continuing current process. The leader propagated basically in a single-channel manner in the first 12 frames after its initiation, producing 8 clear current pulses with a time scale of about 1 μs and a peak current ranging in 2.3∼12.5 kA and an inter-pulse interval in 13.6∼22 μs.

Fig. 6(c) shows a zoom-in view of the first 5 current pulses in **Fig. 6**(b). Similar to the UPL in Case 2, the current pulses of this UNL also presented an oscillation feature, which could be due to the complicated impedance of the tower structure. The leader extended 33.8 m from the tower tip upward in 104 μs, with an average speed ranging in 1.9 ∼ 6.6 × 10^5 m/s and a mean value of 3.2 × 10^5 m/s and a step length ranging in 3.9 to 7.1 m. All these results are well consistent with the previous reports [25].

IV. CONCLUSION

In this study, we introduced in detail the instrumentation setup for simultaneous measurements of electrical current, high-speed camera image and electromagnetic signal of lightning discharges to a newly built 356-m-high Shenzhen Meteorological Gradient Tower (SZMGT) in southern China. With this setup, we had well documented 24 lightning discharges to SZMGT just from April to June of 2019. These are the first set of results on lightning discharges to a tall tower with coordinated current and high-speed camera observations in a lower latitude coastal area in China. Three of them were analyzed in detail to illustrate the initiation and propagation feature of upward leaders from SZMGT: Case 1 - a connecting UPL induced by a DNL in a downward negative discharge, Case 2 - an initial UPL in an upward negative discharge, and Case 3 - a UNL in an upward positive discharge.

For the connecting UPL in Case 1, it was hardly seen by the camera during the initial 2.6 ms of its initiation and propagation but was well ''seen'' by the current shunt with 6 current pulses recorded. The 6 current pulses were with a time scale of ∼1 μs, an inter-pulse time interval of 0.1∼1.5 ms and a peak value of 0.5∼5 kA.

For the initial UPL in Case 2, it extended in step-wise about 16.5 m from the tower tip upward in 5 steps during the first 200 μs after its initiation. The corresponding 5 steps' current pulses were with a time scale of ∼ 1 μs, an inter-pulse time interval of 20∼50 μs and a peak value of 0.5∼2.2 kA. The leader had an average speed ranging from 0.4 to 1.1 × 10^5 m/s with a mean value of 0.8 × 10^5 m/s and a step length ranging from 0.8 to 2.2 m for the 5 steps during the first 200 μs of the leader initiation. Similar results for UPL in rocket-triggered lightning were also observed [19, 20, 22, 23].

For the initial UNL in Case 3, it had a clear stepping and branching signature during the first 200 μs after its initiation. The leader extended 33.8 m from the tower tip upward in 8 steps during the first 104 μs, with a step length ranging from 3.9 to 7.1 m, at speed ranging from 1.9 to 6.6 × 10^5 m/s with a mean value of 3.2 × 10^5 m/s. This was well consistent with the previous result on rocket-triggered-UNL of [25]. The corresponding 8 steps' current pulses were measured with a time scale of 1 μs, a peak value of 2.3∼12.5 kA and an inter-pulse interval of 13.6∼22 μs.

The current pulse peaks for the UNL in Case 3 are much larger than that for the two UPLs in Cases 1 & 2, this might explain that the channel luminosity of the UNL is much stronger than that of the two UPLs. In addition, it was noted that all current pulses in the initial stage of these 3 cases had an oscillation feature, which could be due to the complicated electrical impedance of the tower.

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